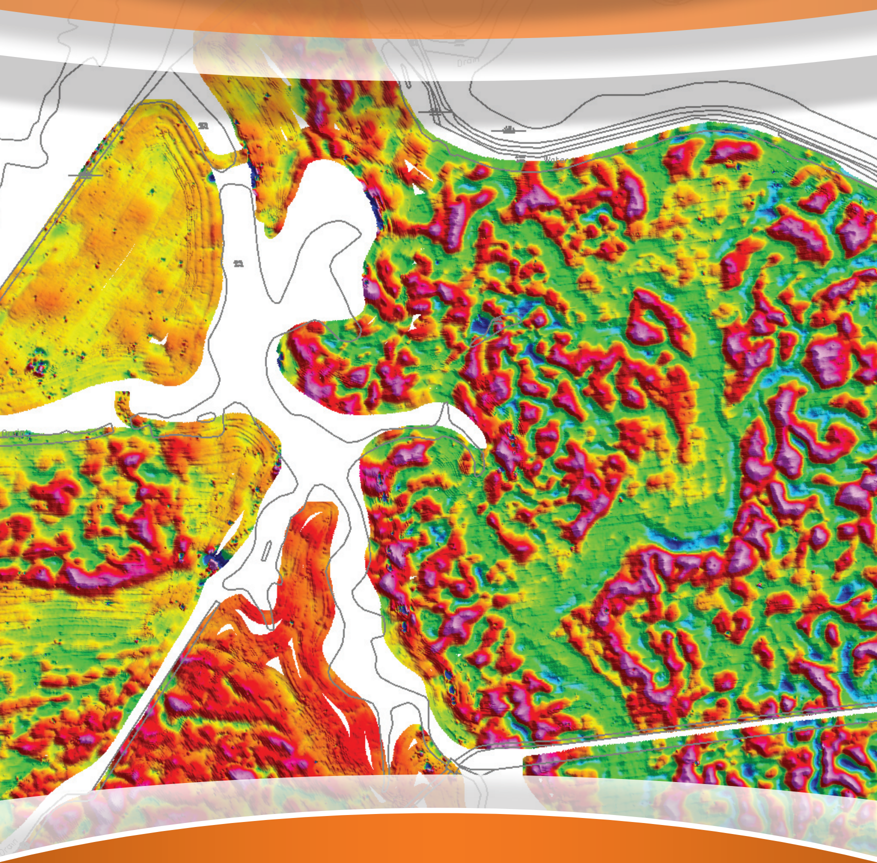
THE GEOLOGICAL FIELD GUIDE SERIES

Field Geophysics

FOURTH EDITION



John Milsom and Asger Eriksen

Field Geophysics

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PREFACE TO THE FIRST EDITION

The purpose of this book is to help anyone involved in small-scale geophysical surveys. It is not a textbook in the traditional sense, in that it is designed for use in the field and concerns itself with practical matters – with theory taking second place. Where theory determines field practice, it is stated, not developed or justified. For example, no attempt is made to explain why four-electrode resistivity works where two-electrode surveys do not.

The book does not deal with marine, airborne or downhole geophysics, nor with deep seismic reflection work. In part this is dictated by the space available, but also by the fact that such surveys are usually carried out by quite large field crews, at least some of whom, it is to be hoped, are both experienced and willing to spread the benefit of that experience more widely.

Where appropriate, some attention is given to jargon. A field observer needs not only to know what to do but also the right words to use, and right in this context means the words which will be understood by others in the same line of business, if not by the compilers of standard dictionaries.

A word of apology is necessary. The field observer is sometimes referred to as 'he'. This is unfortunately realistic, as 'she' is still all too rare, but is not intended to indicate that 'she' is either unknown or unwelcome in the geophysical world. It is hoped that all geophysical field workers, whether male or female and whether geophysicists, geologists or unspecialized field hands, will find something useful in this book.

Finally, a word of thanks. Paul Hayston of BP Minerals and Tim Langdale-Smith of Terronics read early drafts of the text and made numerous invaluable suggestions. To them, to Janet Baker, who drew many of the sketches, and to the companies which provided data and illustrations, I am extremely grateful.

PREFACE TO THE SECOND EDITION

Since the first edition of this book was published in 1989, there have been some changes in the world of field geophysics, not least in its frequent appearance in television coverage of arthaeological 'digs'. In this work, and in surveys of contaminated ground and landfill sites (the archaeological treasure houses of the future), very large numbers of readings are taken at very small spacings and writing down the results could absorb a major part of the entire time in the field. Automatic data logging has therefore become much more important and is being make ever easier as personal computers become smaller and more powerful. New field techniques have been developed and image processing methods are now routinely used to handle the large volumes of data. Comments made in the first edition on the need to record information about the survey area as well as geophysical data have equal, and perhaps even more, force in these instances, but it is obviously usually not practical or appropriate to make individual notes relating to individual readings.

The increase in the number of geophysical surveys directed at the very shallow subsurface (1–5 m) has also led to the increasing use of noncontacting (electromagnetic) methods of conductivity mapping. Moreover, the increased computing power now at every geophysicist's disposal has introduced inversion methods into the interpretation of conventional direct current resistivity soundings and has required corresponding modifications to field operations. It is hoped that these changes are adequately covered in this new edition. a further development has been the much wider availability of ground penetrating radar systems and a recent and fairly rapid fall in their cost. A chapter has been added to cover this relatively new method.

Much else has remained unchanged, and advances in airborne techniques have actually inhibited research into improving ground-based instrumentation for mineral exploration. Automatic and self-levelling gravity meters are becoming more widely available, but are still fairly uncommon. Magnetometers more sensitive than the conventional proton precession or fluxgate instruments are widely advertised, but in most circumstances provide more precision than can be readily used, except in the measurement of field gradients.

VLF methods are enjoying something of a revival in exploration for fracture aquifers in basement rocks, and the importance of ease of use is being recognized by manufacturers. Instruments for induced polarization and time-domain electromagnetic surveys also continue to be improved, but their basic principles remain unchanged. More use is being made of reflected seismic waves, partly because of the formerly undreamed of processing power now available in portable field seismographs, but refraction still dominates seismic studies of the shallow subsurface.

Inevitably, not all the methods currently in use could be covered in the space available. Seismo-electrical methods, in which the source pulses are mechanical and the signal pulses are electrical, are beginning to make their presence felt and may demand a place in textbooks in the future. Few case histories have yet been published. Magnetotelluric methods have a much longer history and continue to be developed, in conjunction with developments in the use of controlled (CSAMT) rather than natural sources, but many general purpose geophysicists will go through their entire careers without being involved in one such survey.

Despite the considerable rewriting, and the slight increase in size (for which I am immensely grateful to the new publishers), the aim of the book remains the same. Like its predecessor it is not a textbook in the conventional sense, but aims to provide practical information and assistance to anyone engaged in small-scale surveys on the ground. In helping me towards this objective, I am grateful particularly to Paul Hayston (RTZ) for introducing me to mineral exploration in a new and exciting area, to Asgeir Eriksen of Geophysical Services International (UK) for keeping me in touch with the realities of engineering and ground-water geophysics, and to my students for reminding me every year of where the worst problems lie. I am also grateful to all those who have given their permission for illustrations to be reproduced (including my daughter, Kate, whose view of field geophysics is shown in Fig. 5.1), and most especially to my wife, Pam, for retyping the original text and for putting up with this all over again.

John Milsom

PREFACE TO THE THIRD EDITION

In the decade and a half since the preparation of the first edition of this handbook there have been few fundamental changes in the methods used in small-scale ground geophysical surveys. There have, however, been radical changes in instrumentation, and far-reaching developments in applications.

The use of geophysics in mineral exploration has declined, both in absolute terms (along with the world-wide decline in the mining industry itself), and relative to other uses. What is loosely termed environmental, engineering or industrial geophysics has taken up much of the slack. Sadly, the search for unexploded ordnance (UXO) is also assuming ever-increasing importance as more and more parts of the world become littered with the detritus of military training and military operations (the much more lethal search for landmines which, unlike UXO, are deliberately designed to escape detection, also uses geophysical methods but is emphatically *not* covered in this book).

Archaeological usage is also increasing, although still inhibited in many cases by the relatively high cost of the equipment.

In instrumentation, the automation of reading and data storage, which was only just becoming significant in the late 1980s, has proceeded apace. Virtually all the new instruments coming on to the market incorporate data loggers and many include devices (such as automatic levelling) to make operations quicker and easier. This, and the fact that virtually every field crew now goes into the field equipped with at least one laptop PC, has had two main, and contrasting, consequences. On the one hand, the need for specialist skills in the field personnel actually operating the instruments has been reduced, and this is leading to a general decline in the quality of field notes. On the other hand, much more can now be done in the field by way of processing and data display, and even interpretation. The change is exemplified by ground radar units, which provide users with visual (even though distorted) pictures of the subsurface while the survey is actually under way. Interestingly, the trend towards instruments that provide effectively continuous coverage as they are dragged or carried along lines has led to the emergence in ground surveys of errors that have long plagued airborne surveys but have now been largely eliminated there. Comments made in the first edition on the need to record information about the survey area as well as geophysical data have equal, and perhaps even more, force in these instances, but it is obviously usually neither practical nor appropriate to make individual notes relating to individual readings.

The increase in the number of geophysical surveys directed at the very shallow subsurface (1–5 m) has also led to the increasing use of electromagnetic methods of conductivity mapping and the development of non-contacting electrical methods which use capacitative rather than inductive coupling. A chapter section has been added to cover this latter, relatively new, method. Other new sections deal with GPS navigation, which has become immensely more useful to geophysicists since the removal of 'selective availability' and with audio-magnetotellurics (AMT), largely considered in the context of controlled sources (CSAMT) that mimic the natural signals but provide greater consistency.

There has also been a slight change in the notes and bibliography. Providing references to individual papers is a problem in a book of this size, and I have actually reduced the number of such references, confining myself to older papers containing some fundamental discussion, and to papers that are the sources of illustrations used. I have also eliminated the section on manufacturers' literature, not because this literature is any less voluminous or important, but because it is now largely available through the Internet. A number of key URLs are therefore given.

Despite the considerable rewriting, and the slight increase in size (for which I am again immensely grateful to the publishers), the aim of the book remains unchanged. Like its predecessors, it is not a textbook in the conventional sense, but aims to provide practical information and assistance to anyone engaged in small-scale surveys on the ground. In helping me towards achieving this objective, I am grateful particularly to Chris Leech of Geomatrix for involving me in some of his training and demonstration surveys, to Asgeir Eriksen of Geophysical Services International (UK) for keeping me in touch with the realities of engineering and groundwater geophysics, and to my students for incisive and uninhibited criticisms of earlier editions. I am also grateful to all those who have given their permission for illustrations to be reproduced (including my daughter, Kate, whose view of field geophysics is shown in Figure 5.1), and most especially to my wife, Pam, for exhaustive (and exhausting) proofreading and for putting up with this for a third time.

PREFACE TO THE FOURTH EDITION

Becoming a co-author of this established handbook on Field Geophysics has been a fascinating exercise, since the changes in emphasis over the years have reflected my own experience. In my company, we moved our main focus from mineral exploration to engineering, environmental and archaeological geophysics in 1993, and have found the wide range of applications in the built environment to be challenging and remarkably satisfying. New routine uses of applied geophysics (e.g. in ballast scanning of railway track-bed) are continually being brought to market. As this new edition goes to press, large productivity gains are being achieved in data collection by using towed array systems, and the potential of remotely monitored, fixed installation geophysical systems to measure changes in material properties is being demonstrated. These are portents of further exciting innovations and developments. There has never been a better time to be involved in applied geophysics.

With the increasing use of geophysical data to provide evidence of change in existing infrastructure and to reduce the in-ground risk when developing new structures, there has come an increased necessity for high levels of professionalism in the collection, management and reporting of geophysical data. The benefits of the growth in data volumes provided by modern data collection systems can only be realised if strict fieldwork procedures are followed. It is no simple task to monitor the quality of data from multi-instrument platforms whilst ensuring both that the positional control meets design specifications and that everything is being kept dry in the pouring rain. Today's field geophysicist has to be a client-friendly, weather-impervious and patient manager of electronics systems, with an eye for detail.

In this edition, new sections on geophysical survey design, procedures, data quality control and limits of detection have been added to emphasise the importance of the fieldwork stage in delivering reliable information to end users. Updates to the resistivity and ground-penetrating radar sections have been made to reflect recent developments. A new chapter on surface wave seismics has been added, partly to increase awareness of this now-active area.

One reason for the decline in the use of small-scale geophysics in mineral exploration has been that the increasing accuracy in three dimensions of GPS positioning, and the parallel reduction in minimum reading times for some instruments, has given airborne data a previously unobtainable quality.

Where small-scale geophysics has expanded, in archaeology, site investigation, other forms of engineering and hydrological investigations and the search for unexploded ordnance (UXO), GPS has also had an impact. Field crews have not only been gifted with a whole range of new tools that will (supposedly) make their lives easier, but have been pointed towards whole new libraries of things that they need to know. In recognition of this fact, a new Chapter 15 is included, to deal with mapping problems and with GPS.

Reluctantly, we have omitted almost all of the sections that, in previous editions, dealt with the geophysical uses of military Very Low Frequency (VLF) radio-wave transmissions. It seems that the military no longer need them. Many transmitters have already been decommissioned, and in many parts of the world it is now impossible to receive adequate signals from even one source, let alone the two, at widely different azimuths, that are required for coverage to be satisfactory. The VLF band is therefore discussed only in the context of broad-band natural and controlled-source magnetotellurics.

Technology has also produced some changes in the book itself. “Field Geophysics” is designed to be taken into the field and used there. As long as the required information is available elsewhere, there therefore seems little point in including a bibliography in the printed edition that would, necessarily, be severely restricted by the space available, and would, inevitably, be listing material unlikely to be available in the field. It is now possible to provide readers with an associated on-line bibliography that is much more comprehensive, and much more searchable, than could ever be possible in print, and this is the route that we have taken. The result will be found on www.wiley.com/go/milsom/geophysics4e. Even there, we have abandoned the referencing of other websites, since these so frequently change or vanish. An internet search engine is all that the reader will need to locate manufacturers’ manuals and applications sheets, to find out about the latest IGRFs or IGFs, or to source SRTM and ASTER topographic grids.

It has been a privilege and a great pleasure to work as a second author with John Milsom on this edition of the handbook.

Asger Eriksen

1
INTRODUCTION

1.1 What Geophysics Measures

Applied or exploration geophysics can be defined as mapping the subsurface through the remote measurement of its physical properties. The discipline dates back to ancient times but only since the advent of modern-day instrumentation has its use become widespread. The development of geophysical techniques and equipment during the early to middle parts of the twentieth century was driven by oil and mineral exploration, for targets that could be several kilometres deep. Many of the instruments used today in archaeological, environmental and engineering surveys owe their development to this kind of geophysics, but have been adapted to investigations of the near-surface, in the range of 0.5–100 m.

The success of any geophysical method relies on there being a measurable contrast between the physical properties of the target and the surrounding medium. The properties utilised are, typically, density, elasticity, magnetic susceptibility, electrical conductivity and radioactivity (Table 1.1). Whether a physical contrast is in practice measurable is inextricably linked to the physics of the problem, the design of the geophysical survey and the selection of suitable equipment. Not all equipment is fit for purpose. Often a combination of methods provides the best means of solving a complex problem, and sometimes a target that does not provide a measurable physical contrast can be detected indirectly by its association with conditions or materials that do. One of the aims of this handbook is to give the field observer an appreciation of the notional detectability of targets and the influence of burial setting, survey design, equipment selection and operating procedures on actual detectability.

1.2 Fields

Although there are many different types of geophysical measurement, small-scale surveys all tend to be rather similar and involve similar, and sometimes ambiguous, jargon. For example, the word *base* has three different common meanings, and *stacked* and *field* have two each.

Measurements in geophysical surveys are made *in the field* but, unfortunately, many are also *of* fields. Field theory is fundamental to gravity,

Field Geophysics, Fourth Edition. John Milsom and Asger Eriksen.

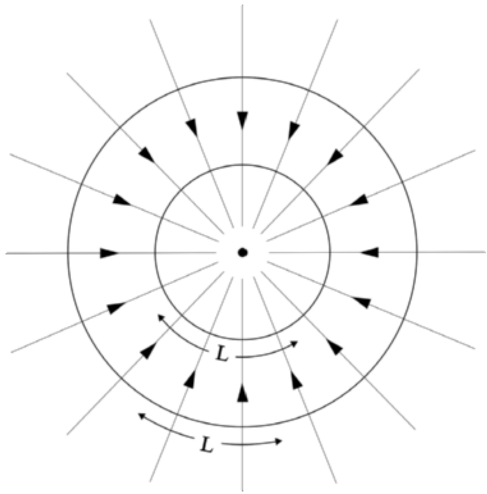

Figure 1.1 *Lines of force from an infinite line source (viewed end on). The distance between the lines increases linearly with distance from the source so that an arc of the inner circle of length L is cut by four lines but an arc of the same length on the outer circle, with double the radius, is cut by only two.*

magnetic and electromagnetic (EM) work, and even particle fluxes and seismic wavefronts can be described in terms of radiation fields. Sometimes ambiguity is unimportant, and sometimes both meanings are appropriate (and intended), but there are occasions when it is necessary to make clear distinctions. In particular, the term *field reading* is nearly always used to identify readings made *in* the field, i.e. not at a base station.

Physical fields can be illustrated by lines of force that show the field direction at any point (Figure 1.1). Intensity can also be indicated, by using more closely spaced lines for strong fields, but it is difficult to do this quantitatively where three-dimensional situations are being illustrated on two-dimensional media.

In Table 1.1 there is a broad division into *passive* and *active* methods. Passive methods use naturally occurring fields (such as the Earth's magnetic field), over which the observer has no control, and detect variations caused by geology or man-made objects. Interpretation is usually non-unique, relying a great deal on the experience of the interpreter. Active methods involve generating signals in order to induce a measurable response associated with

Table 1.1 *Common geophysical techniques*

Technique	Passive/ active	Physical property utilised	Source/signal
Magnetics	Passive	Magnetic susceptibility/ remanence	Earth's magnetic field
Gravity	Passive	Density	Earth's gravitational field
Continuous Wave and Time-Domain Electromagnetics (EM)	Active/ passive	Electrical conductivity/ resistivity	Hz/kHz band electromagnetic waves
Resistivity Imaging/ Sounding	Active	Electrical resistivity	DC electric current
Induced Polarisation	Active	Electrical resistivity/ complex resistivity and chargeability	Pulsed electric current
Self potential (SP)	Passive	Redox and electrokinetic	Redox, streaming and diffusion potentials
Seismic Refraction and Reflection/ Sonic	Active/ passive	Density/elasticity	Explosives, weight drops, vibrations, earthquakes, sonic transducers
Radiometrics	Active/ passive	Radioactivity	Natural or artificial radioactive sources
Ground Penetrating Radar (GPR)	Active	Dielectric properties (permittivity)	Pulsed or stepped frequency microwave EM (50–2000 MHz)
Wireline Logging	Active/ passive	Various	Various

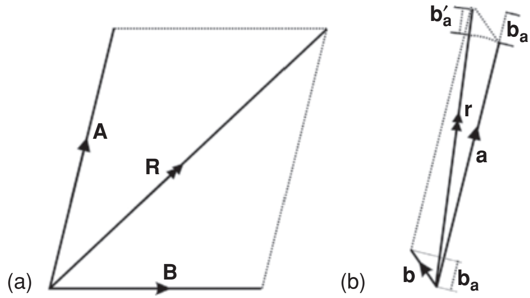

Figure 1.2 *Vector addition by the parallelogram rule. Fields in (a) that are represented in magnitude and direction by the vectors **A** and **B** combine to give the resultant **R**. In (b), the resultant **r** of the large field **a** and the small field **b** is approximately equal in length to the sum of **a** and the component* $\mathbf{b}_a$ *of **b** in the direction of **a**. The angular difference in direction between **a** and **r** is small and therefore the component* $\mathbf{b}'_a$ *in the direction of **r** is almost identical to* $\mathbf{b}_a$.

a target. The observer can control the level of energy input to the ground and also measure variations in energy transmissibility over distance and time. Interpretation of this type of data can be more quantitative. Depth discrimination is often better than with passive methods, but ease of interpretation is not guaranteed.

1.2.1 Vector addition

When combining fields from different sources, vector addition (Figure 1.2) must be used. In passive methods, knowledge of the principles of vector addition is needed to understand the ways in which measurements of local anomalies are affected by regional backgrounds. In active methods, a local anomaly (*secondary field*) is often superimposed on a *primary field* produced by a transmitter. In either case, if the local field is much the weaker of the two (in practice, less than one-tenth the strength of the primary or background field), then the measurement will, to a first approximation, be made in the direction of the stronger field and only the component of the anomaly in that direction will be measured (Figure 1.2b). The slight difference in direction between the resultant and the background or primary field is usually ignored in such cases.

If the two fields are similar in strength, there will be no simple relationship between the magnitude of the anomalous field and the magnitude of the observed anomaly. However, variations in any given *component* of the secondary field can be measured by taking all measurements in a single direction and assuming that the component of the background or primary field in that direction is constant over the survey area. Measurements of vertical rather than total field are sometimes preferred in magnetic and electromagnetic surveys for this reason.

The fields due to multiple sources are not necessarily equal to the vector sums of the fields that would have existed had those sources been present in isolation. A strong magnetic field from one body can affect the magnetisation in another, or even in itself (*demagnetisation effect*), and the interactions between fields, conductors and currents in electrical and electromagnetic surveys can be very complicated.

1.2.2 The inverse-square law

An inverse-square law attenuation of signal strength occurs in most branches of applied geophysics. It is at its simplest in gravity work, where the field due to a point mass is inversely proportional to the square of the distance from the mass, and the constant of proportionality (the *gravitational constant* G) is invariant. Magnetic fields also obey an inverse-square law, and the fact that, in principle, their strength varies with the permeability of the medium is irrelevant in most geophysical work, where measurements are made in either air or water. More important is the fact, which significantly modifies the simple inverse-square law decrease in field strength, that magnetic sources are essentially bipolar (Section 1.2.5).

Electric current flowing from an isolated point-electrode embedded in a continuous homogeneous ground provides a physical illustration of the significance of the inverse-square law. All of the current radiating from the electrode must cross any closed surface that surrounds it. If this surface is a sphere concentric with the electrode, the same fraction of the total current will cross each unit area on the surface of the sphere. The current *per unit area* will therefore be inversely proportional to the *total* surface area, which is in turn proportional to the square of the radius. Current flow in the real Earth is, of course, drastically modified by conductivity variations.

One problem inherent in the inverse-square law control of so many of the fields important in geophysics is *ambiguity*, i.e. the fact that a set of measurements made over a single surface can, in principle, be produced by an infinite number of possible source distributions. Most of these will be geologically impossible, but enough usually remain to render non-geophysical information essential to most interpretations. Figure 1.3 shows two spherical bodies, each with its centre at 5.5 m depth. One, an air void, has a radius of 2.25 m and zero density, whereas the other, a zone of weathered chalk, has a radius of 5 m and a density of 1.9 Mg m^{-3}. The surrounding rock is

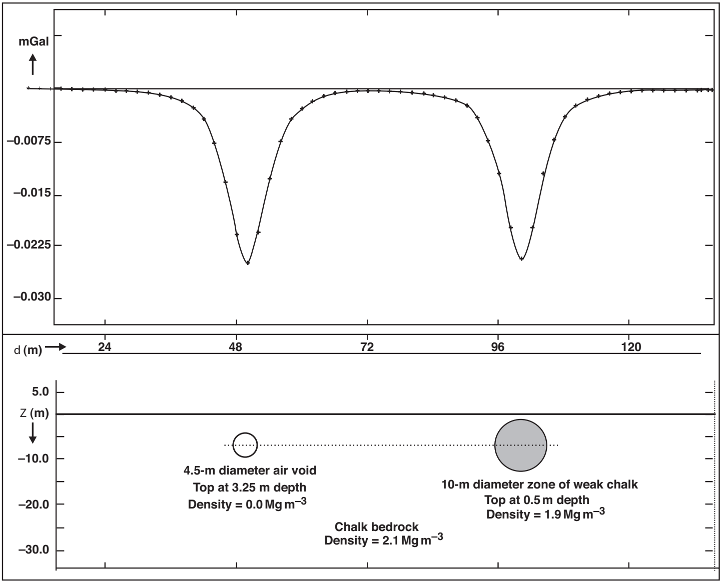

Figure 1.3 *Ambiguity in potential field interpretation. The two very different sources produce almost identical gravity anomalies.*

modelled with the density of 2.1 Mg m^{-3} typical of more competent chalk. The gravitational attraction of each sphere can be calculated assuming the mass deficit is concentrated at its centre. The two anomalies are almost identical, and a follow-on intrusive investigation of each, or a survey using a corroborative geophysical method such as electrical resistivity tomography (Section 6.5) would be required to resolve the ambiguity. Even non-identical anomalies may, of course, differ by amounts so small that they cannot be distinguished in field data.

Ambiguity worries interpreters more than it does the observers in the field, but its existence does emphasise the importance of those observers including in their field notes anything that might possibly contribute to a better understanding of the data that they collect.

1.2.3 Two-dimensional sources

Rates of decrease in field strengths depend on source shapes as well as on the inverse-square law. Infinitely long sources of constant cross-section are

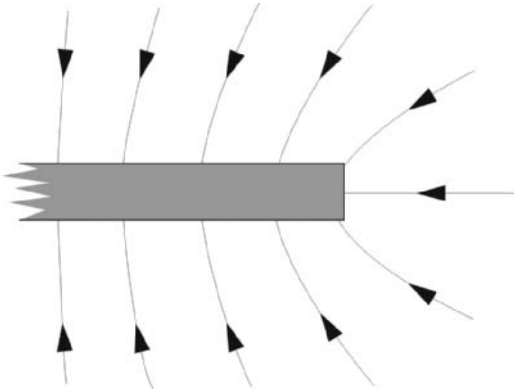

Figure 1.4 *Lines of force from a semi-infinite slab. The lines diverge appreciably only near the edge of the slab, implying that elsewhere the field strength will decrease negligibly with distance.*

termed *two-dimensional (2D)* and are often used in computer modelling to approximate bodies of large strike extent. If the source 'point' in Figure 1.1 represents an infinite line-source seen end-on rather than an actual point, the area of the enclosing (cylindrical) surface is proportional to its radius. The argument applied in the previous section to a point source then leads to the conclusion that the field strength for a line-source will be inversely proportional to distance and not to its square. It follows that, in 2D situations, lines of force drawn on pieces of paper can indicate field intensity (by their separation) as well as direction.

1.2.4 One-dimensional sources

The lines of force or radiation intensity from a source consisting of a homogeneous layer of constant thickness diverge only near its edges (Figure 1.4). The *Bouguer plate* of gravity reductions (Section 2.5.1) and the radioactive source with *2π geometry* (Section 4.3.4) are examples of infinitely extended layer sources, for which field strengths are independent of distance. This condition is approximately achieved if a detector is only a short distance above an extended source and a long way from its edges.

1.2.5 Dipoles

A dipole consists of equal-strength positive and negative point sources a very small distance apart. Its *moment* is equal to the pole strength multiplied

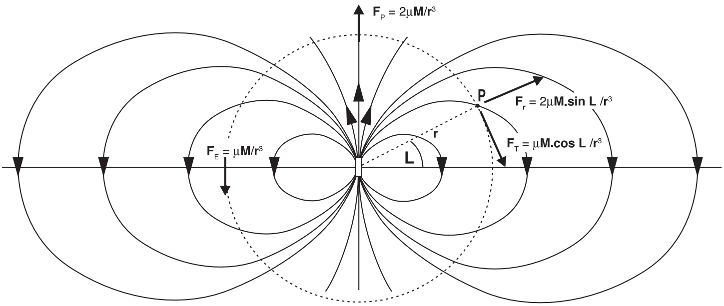

Figure 1.5 *The dipole field. The plane through the dipole at right angles to its axis is known as the equatorial plane, and the angle,* **L**, *between this plane and the line joining the centre of the dipole to any point P is sometimes referred to as the latitude of P. The fields shown, at distances r from the dipole centre, are for a dipole with strength (moment)* **M** *(see Section 3.1.1). The values for the radial and tangential fields at P follow from the fact that* **M** *is a vector and can therefore be resolved according to the parallelogram law. The symbol μ is used for the proportionality constant where magnetic fields are concerned (Chapter 3).*

by the separation distance. Field strength decreases as the inverse cube of distance, and both strength and direction change with 'latitude' (Figure 1.5). The intensity of the field at a point on a dipole 'equator' is only half the intensity at a point the same distance away on the dipole axis, and in the opposite direction.

Magnetisation is fundamentally dipolar, and electric currents circulating in small loops are dipolar sources of magnetic field. Many radar antennas are dipolar, and in some electrical surveys the electrodes are set out in approximately dipole pairs.

1.2.6 Exponential decay

Radioactive particle fluxes and seismic and electromagnetic waves are subject to absorption as well as geometrical attenuation, and the energy crossing closed surfaces is less than the energy emitted by the sources they enclose. In homogeneous media, the percentage loss experienced by a plane wave is determined by the path length and the *attenuation constant*. The absolute loss is proportional also to the signal strength. A similar *exponential* law (Figure 1.6), governed by a *decay constant*, determines the rate of loss of mass by a radioactive substance.

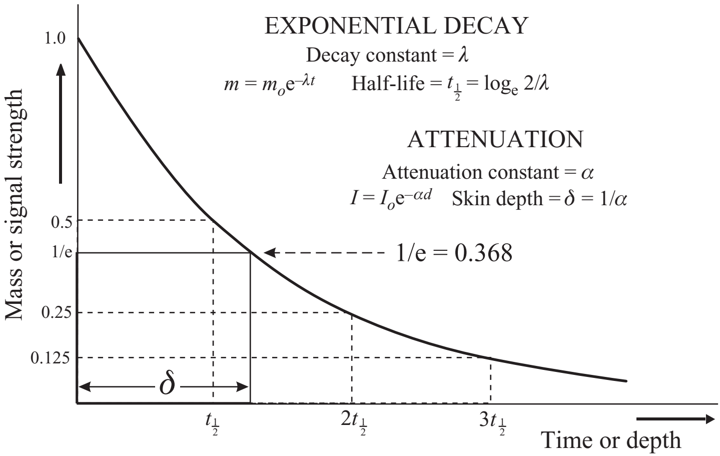

Figure 1.6 *The exponential law, illustrating the parameters used to characterise radioactive decay and radio wave attenuation.*

Attenuation rates are alternatively characterised by *skin-depths*, which are the reciprocals of attenuation constants. For each skin depth travelled, the signal strength decreases to $1/e$ of its original value, where e (= 2.718) is the base of natural logarithms. Radioactive decay rates are normally described in terms of the *half-lives,* equal to $\log_e 2$ (= 0.693) divided by the decay constant. During each half-life period, one half of the material present at its start is lost.

1.3 Geophysical Survey Design

1.3.1 Will geophysics work?

Geophysical techniques cannot be applied indiscriminately. Knowledge of the material properties likely to be associated with a target (and its burial setting) is essential to choosing the correct method(s) and interpreting the results obtained.

Armed with such knowledge, the geophysicist can assess feasibility and, where possible, select a geophysical method to meet the survey objectives. Table 1.2 lists some of the more important physical properties, for some of the commoner rocks and minerals. Inevitably, the values given are no more than broad generalisations, but the table does at least indicate some of the circumstances in which large contrasts in physical properties might be expected, or at least be hoped for.

Table 1.2 *Important physical properties of common rocks and ore minerals*

Material	Density Mg m^{-3}	Susceptibility SI $\times 10^6$	Resistivity Ohm-m	Conductivity mS m^{-1}
Air	0	0	8	0
Ice	0.9	−9	100 000–8	0–0.01
Fresh water	1	0	1 000 000	0.001
Seawater	1.03	0	0.2	5000
Topsoil	1.2–1.8	0.1–10	50–100	10–20
Coal	1.2–1.5	0–1000	500–2000	2–0.5
Dry sand	1.4–1.65	30–1000	1000–5000	1–0.02
Wet sand	1.95–2.05	30–1000	500–5000	0.2–2
Gravel	1.5–1.8	20–5000	100–1000	1–10
Clay	1.5–2.2	10–500	1–100	10–1000
Weathered bedrock	1.8–2.2	10–10 000	100–1000	1–10
Salt	2.1–2.4	−10	10–10 000 000	0.01–1
Shale	2.1–2.7	0–500	10–1000	1–100
Siltstone	2.1–2.6	10–1000	10–10 000	0.1–100
Sandstone	2.15–2.65	20–3000	200–8000	0.125–5
Chalk	1.9–2.1	0–1000	50–200	5–20
Limestone	2.6–2.7	10–1000	500–10 000	0.1–2
Slate	2.6–2.8	0–2000	500–500 000	0.002–2
Graphitic schist	2.5–2.7	10–1000	10–500	2–100
Quartzite	2.6–2.7	−15	500–800 000	0.00125–2
Gneiss	2.6–2.9	0–3000	100–1 000 000	0.001–10
Greenstone	2.7–3.1	500–10 000	500–200 000	0.005–2
Serpentinite	2.5–2.6	2000–100 000	10–10 000	0.1–100
Granulite	2.7–2.9	100–5000	500–1 000 000	0.001–2
Granite	2.5–2.7	20–5000	200–1 000 000	0.001–5
Rhyolite	2.5–2.7	100–5000	1000–1 000 000	0.001–1
Basalt	2.7–3.1	500–100 000	200–100 000	0.01–5
Dolerite	2.8–3.1	500–100 000	100–100 000	0.01–10
Gabbro	2.7–3.3	100–10 000	1000–1 000 000	0.001–1
Peridotite	3.1–3.4	10–10 000	100–100 000	0.01–10
Pyrite	4.9–5.0	100–5000	0.01–100	10–1 000 000
Pyrrhotite	4.4–4.7	1000–50 000	0.001–0.01	1 000 000–10 000 000
Sphalerite	3.8–4.2	10–100	1000–1 000 000	0.001–1
Galena	7.3–7.7	10–500	0.001–100	10–10 000 000
Chalcopyrite	4.1–4.3	100–5000	0.005–0.1	10 000–200 000
Chromite	4.5–4.7	750–50 000	0.1–1000	1–10 000
Hematite	5.0–5.1	100–1000	0.01–1 000 000	0.001–100 000
Magnetite	5.1–5.3	10 000–10 000 000	0.01–1000	0.001–1
Cassiterite	7.0–7.2	10–500	0.001–10 000	0.1–10 000 000

The design and implementation of a geophysical survey requires careful consideration of the following main factors:

(a) *Target discrimination*
The nature and degree of the contrast in physical properties between a target and its surroundings is of primary importance in the feasibility assessment and choice of techniques. However, information may be limited or non-existent, and in these cases the geophysicist should recommend a trial survey or the application of multiple techniques. Trials are recommended wherever the assumptions made in designing the survey are suspect. Usually a day is all that is required to determine whether the chosen methods can detect the presence of a target in actual field conditions. This is an often neglected stage in the execution of a geophysical survey but is one that could save much geophysicist's pride and client's money were it more routinely used.
Once it has been decided, on the basis of observation, modelling and/or experience, what the geophysical response of a buried target is likely to be, the sensitivity of the equipment and the distribution of the survey stations needed to meet the survey objectives can be specified.

(b) *Detection distance*
In addition to the composition of the target and its surroundings, geophysical methods are sensitive to the relationship between target size and detection distance. In general, the greater the depth of the target, the larger its volume and/or cross-sectional area must be for it to be detectable.

(c) *Survey resolution*
The choice of sampling interval (frequency or spacing of sampling points) is critical to the success of a survey and its cost-effectiveness. The appropriate interval is dictated by the geophysical 'footprint' of the target, which may be tens of centimetres for small-diameter shallow pipes, a few metres for narrow fault zones, and kilometres for ore bodies at depth. An anomaly must be adequately sampled to meet the survey objectives. Although it is almost equally important that resources are not wasted in collecting more data than are required, it has to be remembered that under-sampling can produce completely fictitious anomalies (Figure 1.7).
In some cases, particularly on brownfield sites, surface obstructions can prevent the collection of regularly spaced data. The obstructions may be removable, but unless their impact on the survey outcome is fully understood by the field observer, they may not be dealt with at the appropriate time.

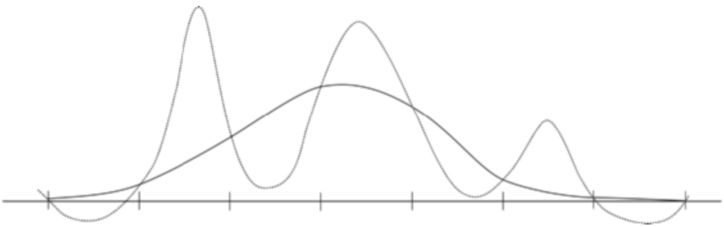

Figure 1.7 *Aliasing. The dashed curve shows a magnetic profile as it should have been recorded, the solid line shows the spurious anomaly that would be deduced by using only data from the widely spaced reading points indicated by vertical lines on the distance axis. Aliasing can occur in time as well as in space, if time-varying signals are sampled too infrequently.*

(d) *Site conditions*
The suitability of a site for collecting good quality geophysical data is often overlooked in survey design. The issues affecting data quality that could be of concern are often specific to the method or methods being proposed. For example, signal degradation may occur or geophysical 'noise' may be introduced in electromagnetic and magnetic surveys by the presence of surface metallic structures and overhead power lines. In microgravity or seismic surveys, noise may result from traffic movements or wind and waves. If the noise exceeds the amplitude of the anomaly due to the target and cannot be successfully removed, the target will not be detectable. The best way to assess the likely influence of site conditions is to visit the site at the design stage and/or carry out a trial survey.

Field observers should be fully briefed on the objectives of the survey and mindful of the design aspects, so that departures of the field conditions from any assumptions made can be reported in good time, allowing the design to be modified where possible. They should immediately report any unexpected conditions, and any geological information provided by drillers to which the geophysicist who designed the survey may not have been privy. They may also obtain useful information relating to previous land-use in conversations with the client or casual passers-by, and this also should be passed on.

1.3.2 Preparing for a survey

The design of a regional or even a local geophysical survey can be greatly assisted by using the geographic data now freely available on the internet.